FIELDNOTES
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MAJOR ARIZONA SALT DEPOSITS

by H. Wesley Peirce

INTRODUCTION

Although not commonly known, rocksalt, ordinary sodium chloride, is very much a part of Arizona. It has accumulated in some places to thicknesses greater than the Grand Canyon is deep! From a geologic point of view, some of the state's rocksalt deposits are believed to be unique in North America, if not the world. As a rock, salt functions as an important component of Arizona's geologic foundation. From a human perspective, rocksalt can be either an asset or a liability; in Arizona, it is both.

This article summarizes what we have come to learn about salt deposits in Arizona. It should be pointed out that our focus is on *large* deposits and not the smaller, exposed occurrences that were exploited by aborigines.

BACKGROUND

The word *salt* is used here to mean a rock made from the natural aggregation of the sodium chloride mineral, halite. Most natural waters contain some sodium chloride in solution. Not only does this chemical come in small amounts from the weathering of common rock materials, but also from oceans via atmospheric circulation and rainfall (rainwater is *not* pure). Wherever waters gather and evaporate, mineral salts form. Large salt deposits require, over time, the evaporation of huge volumes of water. Thus, thick salt deposits, whether formed in interior lakes or ocean waters, require repeated cycles of inflow and evaporation. Once formed, special conditions are essential to preserve these readily soluble salt deposits from subsequent dissolution. Natural dissolution of subsurface salt can have deleterious physical and/or chemical effects.

DISCOVERY AND RECOGNITION

All of Arizona's large salt deposits were initially encountered during the course of exploration drilling for other substances. The first discovery seems to have been in 1920 during petroleum exploration drilling near Holbrook in the Colorado Plateau Province of northern Arizona. Since this initial discovery, many additional drill holes in the Holbrook region have penetrated salt. As a consequence, this particular occurrence is now reasonably well-outlined and understood (Figure 1, no. 1).

In the Basin and Range Province of southern Arizona, major discoveries took place from 1957 to 1968. In these cases the number of penetrations by drilling are few; therefore, deposit details are lacking. These latter discoveries are recent enough to have escaped the publicity needed to make their existence a matter of common knowledge. Most likely, additional deposits exist within this province.

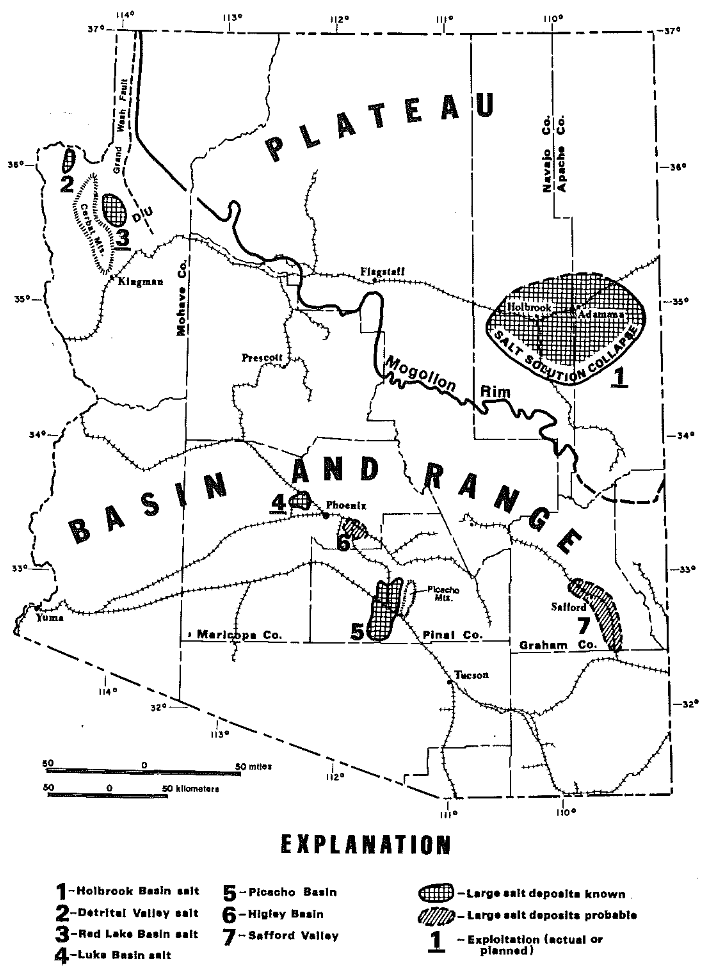

Figure 1. Index to Arizona Salt Deposits and Location of Railroads.

COLORADO PLATEAU DEPOSITS

The largest salt deposits of the Colorado Plateau Province occur near Holbrook. Salt, in beds or layers within the Supai Formation, occurs in the subsurface of southern Navajo and Apache Counties beneath a region approximating 2,300 square miles in size (Figures 1 and 2). The area of thickened Supai Formation, within which

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salt and other evaporites are associated, is frequently called the Holbrook Basin. The principal salt deposits, associated with other sedimentary rocks, occur as discontinuous units or zones within the stratigraphic interval between the Fort Apache Limestone Member of the Supai Formation below and the Coconino Sandstone above (Figure 2). Over the region, this stratigraphic interval ranges in thickness between 450 and 1,300 feet. The salt occurs within the thicker, or basinal, parts. Depths to the top of the evaporite interval, marked by an anhydrite-gypsum (calcium sulfate) zone, range from 600 to 2,500 feet, the deepest portions being in the northeastern part of the basin. Indications are that the principal concentration of salt occurs in a zone 400 feet thick within the upper half of the evaporite interval, along a northeast-trending belt that is about 55 miles in length (Peirce, 1969).

More than 150 drill holes have encountered either part or all of the Supai salt section (Peirce and Scurlock, 1972). Many of these were drilled in 1964–65 during an intensive effort to outline commercial deposits of associated potash in the form of sylvite (potassium chloride). The potash drilling outlined an area of about 300 square miles that is underlain by a potash zone that occurs at depths ranging from 700 to 2,000 feet and within the upper 150 feet of the evaporite section. Although only low-grade deposits were identified, changing economics and supply patterns could one day render these deposits of interest to the state and nation [sylvite is the principal source of potassium, an essential element in plant growth, and is extensively used in agricultural fertilizers]. A significant portion of the mineral rights are held by the State of Arizona.

A subsurface storage facility has been developed along the Santa Fe Railroad at Adamana (Figure 1). Liquid petroleum gas (LPG) products, propane and butane, produced at oil refineries, are held in eleven cavities that were created by dissolving salt. These cavities are developed between 900 and 1,200 feet beneath the surface, and, because of relative thinness of the salt beds, they are elongated horizontally. The company operates as a storage facility for other energy companies. Whereas propane is burned directly for heat, butane is added to winter gasoline supplies to assist in cold weather starting. Because of the seasonal usage, butane must be stored during the hotter season. Propane is stored, in part, for distribution to rural markets in northern Arizona. These products come from a combination of California, New Mexico and Texas refineries, by truck and rail. Of the eleven cavities, three are presently used for propane, and eight are used for butane. Future expansion of this facility is anticipated.

An interesting environmental impact of the Supai salt interval is sink hole development that results from salt solution and surface collapse. Sink holes on the Mogollon Slope have long been known. Depression contours are widespread on topographic maps of both southern Navajo and Apache Counties. Darton (1925) called attention to sinks in this region, and rather casually related them to a classic explanation—the solution of a shallowly buried limestone. Subsequently, the few geologists aware of these phenomena have agreed that the sinks are caused by the solution of salt in the subsurface. There is a feature west of Snowflake known as Dry Lake Valley, a basin of internal drainage. This valley covers an area of at least 120 square miles and almost certainly represents collapse above a major zone of salt dissolution (Bahr, 1962; Peirce and Wilt, 1970). The uppermost part of the salt-bearing Supai section appears to underlie the valley at a depth approximating 600–700 feet. It is suspected that the regionally extensive development of variably sized depressions with internal drainage is directly related to the solution of salt in the areas where salt probably occurs within 1,000 feet of the surface.

It seems likely that this process is continuing, although at an unknown rate. Bahr (1962, p. 18) makes this statement: "That solution is a continuing factor in the structural development of the area (Dry Lake) is evidenced by the appearance of several deep sinks on air photos flown in 1953, which are absent on photos flown only 17 years earlier."

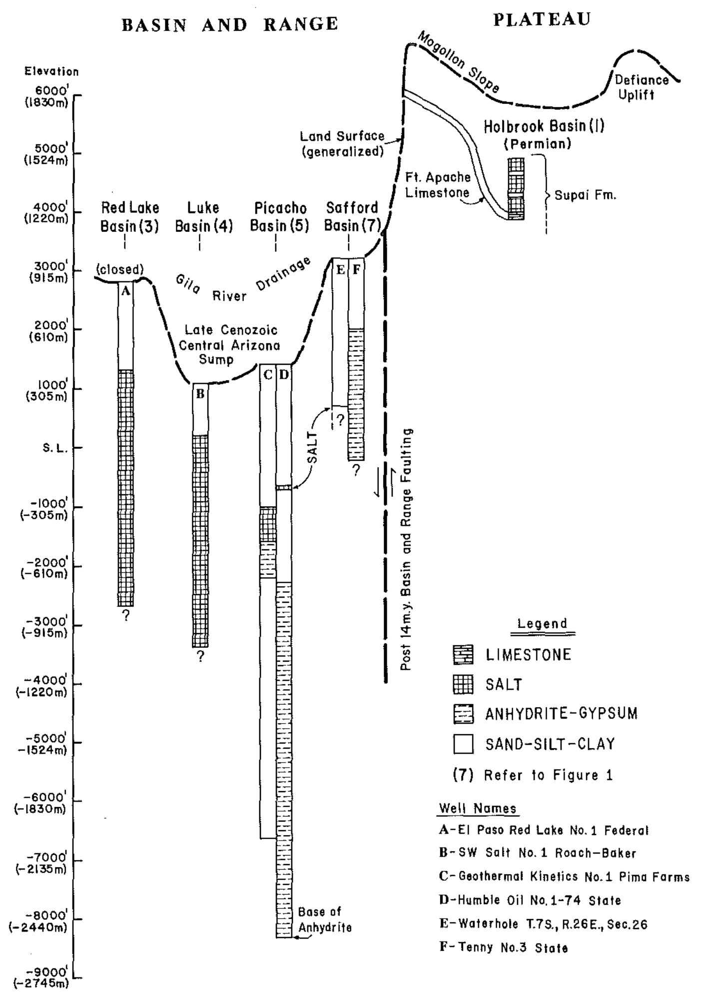

Figure 2. Geologic Setting of Arizona Salt Deposits in the Basin and Range and Colorado Plateau Provinces.

The southern edge of the Supai evaporites defines a belt that is at least 50 miles in length. The solution-collapse process has significant land use implications for the region and appears to warrant more attention than it has thus far been given.

A preliminary report (Mytton, 1973) evaluates the Supai salt as a possible target for the development of either a noxious waste or a radioactive waste disposal site. The evidence of salt solution was a significant factor in urging caution in future waste storage considerations. Another report (Johnson and Gonzales, 1978) includes the Supai salt in a nationwide survey of salt deposits potentially suitable for radioactive waste storage. They, too, urge a very close look at the salt dissolution question prior to any serious consideration of using this salt as a radioactive waste storage site.

BASIN AND RANGE DEPOSITS

Perhaps the most intriguing salt deposits are those that have been encountered in relatively recent times in the Basin and Range country. Although their existence is known, little detail about each is available. Because our scientific knowledge about these deposits remains so general, there is room for debate and legitimate differences in opinion concerning their age and manner of origin. All of the deposits occur beneath valley or basin floors, and were first encountered by drilling.

Detrital and Hualapai Valleys

In extreme northwestern Arizona there are two salt occurrences just south of Lake Mead in Mohave County (Figure 1). One is the

Detrital Valley deposit (Figure 1, no. 2) and the other is the Red Lake deposit beneath Hualapai Valley (Figure 1, no. 3).

A dozen or more exploration holes have been drilled in Detrital Valley over an area of several square miles south of Lake Mead (Peirce, 1969; 1974). Bedded salt occurs from 300 to 800 feet beneath the surface and attains a maximum thickness of about 715 feet above nonsalt rocks. It is believed that the salt and associated gypsum-anhydrite-clastics belong to the Miocene Muddy Creek Formation. This formation crops out around Lake Mead and, in Arizona, includes outcropping evaporite in the form of gypsum. Outcrop elevations of gypsum are consistent with evaporite tops in Detrital Valley drill holes.

Whereas the Detrital Valley salt is less than 1,000 feet thick, the Red Lake deposit is at least 4,000 feet thick and could be as thick as 10,000 feet [for comparison, the Grand Canyon is generally less than 6,000 feet deep]. Only three exploration holes provide direct data about this salt. Both geologic and geophysical information combine to assist in formulating a generalized concept of what this salt body represents. Considering that the volume of salt likely exceeds 100 cubic miles, there is interest in seeking an explanation for it. This author's views have been expressed elsewhere (Peirce, 1972; 1976) and will only be summarized here.

Hualapai Valley contains Red Lake Playa, one of two remaining, sizable basins of internal drainage in Arizona (Willcox Playa is the other). Geophysical data demonstrate rather clearly that the Red Lake basin is closed on all sides with a buried bedrock sill at its northern end. The deposit may be on the order of 12 miles long (parallel to the length of the valley), five miles wide and two miles thick. The elevations of the evaporite and/or salt tops are similar to those in Detrital Valley and in outcrop on the south side of Lake Mead. The indicated conformance of the deposit and associated strata to the overall basin shape, and suspected affinity with the nonmarine Muddy Creek Formation, strongly suggest a genesis related to the origin of the basin itself. The buried sill of bedrock at the north end combines with all else to suggest that the Red Lake Basin has all of the earmarks necessary to have been a classic basin of salt accumulation.

One boundary of this basin is the margin of the Colorado Plateau Province—the other is the Cerbat Mountain range block (Figure 1). This disruption of geologic continuity is a manifestation of the Basin and Range disturbance (faulting) that took place subsequent to about 13 million years ago (Stanley and Eberly, 1978; Scarborough and Peirce, 1978) in late Miocene time. Salt deposition was accommodated by an actively subsiding basin. The model suggests that the salt is thick, nonmarine and late Cenozoic in age, and represents an Arizona salt deposit type that is unique in the United States, and perhaps even the continent. Other large North American salt deposits are older and most are marine in origin (Johnson and Gonzales, 1978).

The Red Lake deposit is buried by at least 1,500 feet of other sedimentary materials. There is no suggestion that either salt movement or salt solution have affected the ground surface.

Major transportation arteries pass by the southern end of Hualapai Valley. These include a railroad, a major interstate highway and a gas line. There are no such deposits recognized in either California or Nevada. Because of these factors, Southwest Gas Co. is planning to construct a natural gas storage facility in this salt (Peirce, 1981). Cheap storage in man-made solution cavities will enable the company to respond more effectively to winter-time peaking demands in Las Vegas and vicinity. The deposit is large and could eventually be utilized by other interests. Both federal and state ~~lands are~~ involved.

Salt River Valley

In 1970 the Southwest Salt Company drilled 3,600 feet of salt in Maricopa County west of Glendale and just east of Luke Air Force Base (Figure 1, no. 4). This area has come to be referred to as the Luke Salt, and the envisioned basin in which the salt accumulated, as the Luke Basin. Only a few holes penetrate into salt; however, not one penetrates the entire thickness of the deposit. As with the Red Lake occurrence, there is little direct data about the overall salt deposit. Again, geophysical information, especially gravity studies (Peterson, 1968) suggest that the salt, with minor clastic interbeds, could be as thick as 10,000 feet. The top of the deposit is 880 feet beneath the ground surface where Southwest Salt first drilled (Figure 2, Well B). Although details are lacking, it is estimated that this deposit could contain on the order of 30 cubic miles of halite. It is smaller than Red Lake in areal extent, but otherwise appears analogous in many ways.

Ideas about the origin and history of this salt deposit vary. Eaton and others (1972) suggest that the Luke Salt could represent a diapiric intrusion (i.e., an oozing, vertical flow of a plastic substance, such as salt), and could thus be a salt dome similar to occurrences along the U.S. Gulf Coast. However, they also concede that it could be an "*in situ* evaporite facies of the valley-fill section," in which the uppermost part has been somewhat plastically deformed or domed. Peirce (1974) suggests that there is evidence for at least 600 feet of upward salt movement. However, he subscribes to the idea that the salt was originally deposited in a local structural basin in late Cenozoic time (Peirce, 1976).

The Luke Salt is being utilized in two basic ways: 1) production of solar salt in evaporation ponds, and 2) the storage of propane and butane in man-made solution cavities. The storage facility presently consists of three cavities, each shaped like an inverted carrot, and each capable of holding 30 million gallons of LPG. The length of each cavity is 1,000 feet, oriented vertically; the maximum width is about 70 feet. The facility is served by a nearby railroad spur where facilities allow loading and unloading through a system of pipes. Brine is used to maintain appropriate pressures and to protect cavity walls [hydrocarbon products do not react with salt].

Earth cracks occurring near the surface evaporating facility pre-exist its establishment. The region is farmed and the cracks are believed to be related to groundwater withdrawal and subsequent surface subsidence. The salt deposit represents a subsurface discontinuity around which dewatered sediments tend to differentally compact and crack. Here the salt acts just like bedrock does in the subsiding Picacho region (Laney and others, 1978; Peirce, 1979).

Rights to produce and utilize this salt are obtained by the acquisition of a sodium lease from the federal government.

Picacho Basin

In 1973 Humble Oil and Refining Co. drilled a deep test hole near Picacho (Figure 1, no. 5; Figure 2, Well D). The geologic highlights of this test were presented by Peirce (1974). Of particular interest is the presence of a vertical interval of 6,000 feet that consists largely of anhydrite ($CaSO_4$), another type of evaporite. Some salt (less than 100 feet) was drilled at a depth of about 2,100–2,200 feet. A volcanic rock unit that is isotopically dated at 15 million years lies 700 feet beneath the evaporite sequence (Shafiqullah and others, 1976). Thus, this basin-filling sequence is considered to be late Cenozoic in age—a product related to the Basin and Range disturbance, a faulting event that framed many of southern Arizona's ranges and valleys. The basinal feature is referred to as the Picacho Basin. Although there are few definitive drill holes, geophysical data suggest basin shape and dimensions. It is about 30 miles in length, nine miles in width, and trends just east of north, parallel to the west side of the Picacho Mountains (Figure 1).

About five or six miles northwest of the Humble hole, Geothermal Kinetics, Inc., in 1974, drilled an 8,000 foot test in the Picacho Basin (Figure 2, Well C). Drilling records suggest that, although the overall evaporite section is much thinner, the section of salt is thicker. Whereas the overall evaporite section is on the order of 1,500 feet thick, the upper 600–700 feet is believed to be salt. Considering the indicated size of the Picacho Basin, these brief clues suggest that the potential for the occurrence of an abundance of salt is high.

Many transportation arteries cross the southern end of the Picacho Basin. Should low-cost subsurface storage in salt become of interest between Phoenix and Tucson, the Picacho Basin is a likely region to explore.

The Picacho country is a major agricultural region that utilizes large volumes of groundwater. It is germane to speculate on the extent to which the near-surface fresh water zone is limited downward by saline materials, a question that can be asked about much of southern Arizona's groundwater-dependent region.

Other Occurrences and Potential

Geophysical studies and some drilling data indicate that deep basins underlie many of the valleys of southern Arizona (Oppenheimer and Sumner, 1980). This is to say that the valleys are underlain by thick-to-thicker sequences of relatively low-density sedimentary rocks that overlie more dense rocks. As has been shown, these sedimentary materials, in places, include evaporite materials such as salt. Many of the basin-filling sequences remain largely untested, and, therefore, there is potential for additional salt and related rocks.

In 1973 a 9,000 foot geothermal test was drilled in Maricopa County, about eight miles east of Chandler. The sedimentary section at the site is about 7,000 feet thick and includes evaporite strata over an interval of 1,500 feet. Anhydrite is the principal evaporite, but some salt could be present and have remained undetected because of solution of drill cuttings prior to sample recovery. Geophysical studies suggest that the sedimentary section significantly thickens west of the drillsite, indicating a center of deposition in that direction. Significant salt could be present nearer the depocenter four to five miles east of Chandler. The top of the anticipated evaporites could be nearly 2,300 feet beneath the surface. This inferred depositional center is called the Higley Basin (Figure 1, no. 6).

The San Simon Valley of Graham County is one of southeastern Arizona's very long valleys and the Gila River occupies a portion of it. Unfortunately, despite its size, there is no deep drilling within the valley. Geophysical data suggest that it has zones within it that contain basin-fill sediments that are several thousands of feet thick, perhaps as much as 10,000 feet.

In 1971 a relatively shallow hole was drilled to a depth of 3,500 feet, about 20 miles south of Safford. Incomplete records suggest that the hole penetrated gypsum and/or anhydrite in the interval 1,200–3,500 feet (a thickness of 2,300 feet). The hole terminated in the evaporite. Therefore, there is no present way of knowing the true extent and nature of the complete evaporite sequence. About four miles west of Safford a hole, drilled in search of water, returned core samples that contain discrete halite (salt) in mudstone from a depth of about 2,300 feet (Figure 2, Well E). These clues suggest that the depths of San Simon Valley could contain significant quantities of salt and related substances.

GENERAL CONCLUSIONS

Though not widely recognized, Arizona's geologic framework contains large, subsurface deposits of rocksalt. Some of these deposits appear to be unique in North America, and, no doubt, others remain to be discovered. The fact of their existence is potentially both a regional asset and a local liability. They can be constructively utilized as a source of salt products, as well as a medium for cheap, convenient storage of certain nonreactive materials. However, their solubility in fresh water can lead to potentially destructive effects, as evidenced in the Mogollon Slope collapse belt.

It is significant to note that, in several areas, rocksalt underlies the freshwater aquifer systems of Arizona valleys or basins. The extent to which rocksalt constitutes a limiting factor in the development of future potable groundwater reserves remains to be evaluated.

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Wes Peirce has been with the Bureau of Geology twenty-five years. During that time, he has witnessed the emergence of an environmental-ecological awareness and an increased public demand for knowledge about the earth. He has also seen the increase and expansion of federal-support programs, resulting in grant monies for supplementary staff and for on-going geologic projects.

Peirce's general areas of interest and familiarity involve the geologic history of Arizona, the impact of Arizona geology on land use, and the ecological significance of things geologic. Because of the public demand for geologically related services, in conjunction with a small operating staff, Wes advocates the necessity of a multi-disciplinary, versatile, generalist approach to things geologic.

Wes received his Ph.D. in geology from the University of Arizona in 1962, his M.S. in 1952 from Indiana University, and, a B.S. from the University of Montana (1949).

The following are some of the diverse publications prepared by Wes Peirce.

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ANNOUNCEMENT

Dallas Peck was appointed the 11th director of the 101-year-old U.S. Geological Survey in June 1981. Dr. Peck began his career as a geologist with the USGS in 1951. As director he currently commands a post in Reston, Virginia, overseeing 9,000 federal employees in almost 300 field offices nationwide.

POSITION AVAILABLE

GEOLOGIST (Search Re-opened)

The Bureau of Geology and Mineral Technology, Geological Survey Branch, a division of the University of Arizona, invites applications for a tenure-track geologist position. The person selected will contribute to the basic understanding of the geological setting of the State of Arizona with special attention to the stratigraphic and structural control of mineral and energy resources. Preferred qualifications include geologic field experience in the Southwest with emphasis on economic geology and geologic mapping. Ph.D. or comparable experience required.

This is an Academic Professional position that carries with it appointment to the organized research and service staff of the University of Arizona. Position title is Assistant Geologist, which is roughly comparable to Assistant Professor. Salary, in the low to middle 20s, will be based on the 12-month appointment range of an academic faculty member. Full position description is available on request. Send letter of application, resume, and names and addresses of 3-5 references to Dr. Larry D. Fellows, Bureau of Geology and Mineral Technology, 845 N. Park Ave., Tucson, AZ 85719 before February 1, 1982.

Geothermal Commercialization

by Larry Goldstone

The Arizona Geothermal Commercialization Team, which began in the Department of Chemical Engineering at the University of Arizona in 1977, has been funded by the U.S. Department of Energy, and administered by the Arizona Solar Energy Commission. Since its inception, the Team's main goal has involved basic research and evaluation regarding future geothermal energy development in Arizona—to develop means to reduce energy costs, reduce dependence on fossil fuels and reduce water consumption.

Twenty-two general uses for geothermal energy had been proposed after the first year's research. These uses include space heating and cooling, mining, desalinization, greenhousing, irrigation pumping, crop drying and sugar beet processing.

Since the first year of the project, research has continued to determine the most promising geothermal resource uses, e.g., 1) the use of low temperature heat in the mining industry for extraction and refinement of copper, 2) space heating and cooling for residential, commercial and industrial users, 3) irrigation pumping and biosalinity agriculture, 4) alcohol production, and 5) food processing. Research into particular uses has centered on the applicability to a users' operation, rather than on solving technical problems that could accompany certain operations. For this reason, geothermal energy is currently considered to be a potential energy alternative.

Secondly, the Team has devised Area Development Plans for seven regions in Arizona. Each development plan provides essential background material on population growth, current energy use, water availability, land ownership, resource locations and characteristics, industrial growth, identification of industrial and agricultural operations suitable for geothermal use, and energy price projections. In addition, each plan culminates with a list of colocated users (i.e., users adjacent to suspected geothermal resources), and with projections regarding future potential for geothermal energy within each region.

A third area of involvement for geothermal energy development is comprised of legal, regulatory and institutional considerations. Existing legislation within Arizona, regarding the development of geothermal resources, has created a series of regulations and permit procedures. The Team has therefore compiled an Institutional Handbook on geothermal development. The handbook defines procedures necessary for the following: acquiring state, Indian, federal and private land; obtaining permits necessary to drill wells for geothermal energy production and injection; listings of health agency requirements; and review by regulatory authorities.

The Commercialization Team is currently working with the state legislature to alleviate three potential problem areas. First, recent passage of the Groundwater Management Act, and associated provisions that designate Active Management Areas, could possibly hamper geothermal development in critical groundwater areas. Second, methods for calculating royalty payments for geothermal development on state land are not clearly defined. In certain cases, royalty payments may be so excessive that geothermal development would not be economical. Lastly, the current tax structure in Arizona offers no incentives for geothermal development. For example, if a developer would be interested in using an alternative energy source, he might be better off choosing solar energy simply because of the availability of tax credits for solar development. It is hoped that these and other problems can be clarified in the future in order to provide a more certain institutional framework for geothermal energy development in Arizona.

In summary, geothermal energy development, although a viable energy option, requires much more than the existence of geothermal resources. It has been the goal of the Geothermal Commercialization Team to facilitate resource data and to encourage development of geothermal alternatives by addressing relevant technical, legal and economic questions. To date, there are no geothermal resources currently in use in Arizona. However, it is hoped that the work that has been performed by the Geothermal Commercialization Team will provide the necessary groundwork for the future.

Larry Goldstone attended New Mexico State University and obtained a B.A. in Economics in 1978, followed by a M.B.A. degree from the University of Arizona in 1980. He became involved in the Geothermal Commercialization Team in 1978, and is currently the project manager of the Team.

RECONNAISSANCE GEOLOGY:

by Robert B. Scarborough

The Bureau has completed a reconnaissance geologic mapping project along a narrow strip bordering the lower Salt River, starting just below Roosevelt Dam and extending downstream to Granite Reef Dam, a distance of about 45 river miles. The project was sponsored by the U.S. Bureau of Reclamation (Boulder City, Nevada) as an aid in planning future reclamation projects 'along this stretch of the Salt River.

Although various published and unpublished reconnaissance geologic maps exist in the region (see listing in Sheridan, 1978), no single map exists which displays the general geology of the entire stretch in sufficient detail for evaluation and planning purposes.

In addition to the mapping, potassium-argon age dates of six volcanic rocks were determined by personnel of the Laboratory of Isotope Geochemistry at the University of Arizona.

Field work was carried out between November 1980 and April 1981, in about 35 field days. Because of the rugged nature of the area, much of the work was conducted out of boats on Saguaro, Canyon and Apache Lakes. Some of the more inaccessible areas required the use of a helicopter. Much of the geology is beautifully exposed along the gorge of the Salt River, where it has cut through the stratified rocks of the northern Superstition volcanic field. Upstream from Horse Mesa Dam, the cliffs stand 2,100 feet above Apache Lake. The four lakes along the lower Salt River—Saguaro, Canyon, Apache, and Roosevelt—not only furnish water and hydroelectricity for the metropolitan Phoenix area, but also provide a grand access to the side canyons of the Superstition and the southern Mazatzal Mountains.

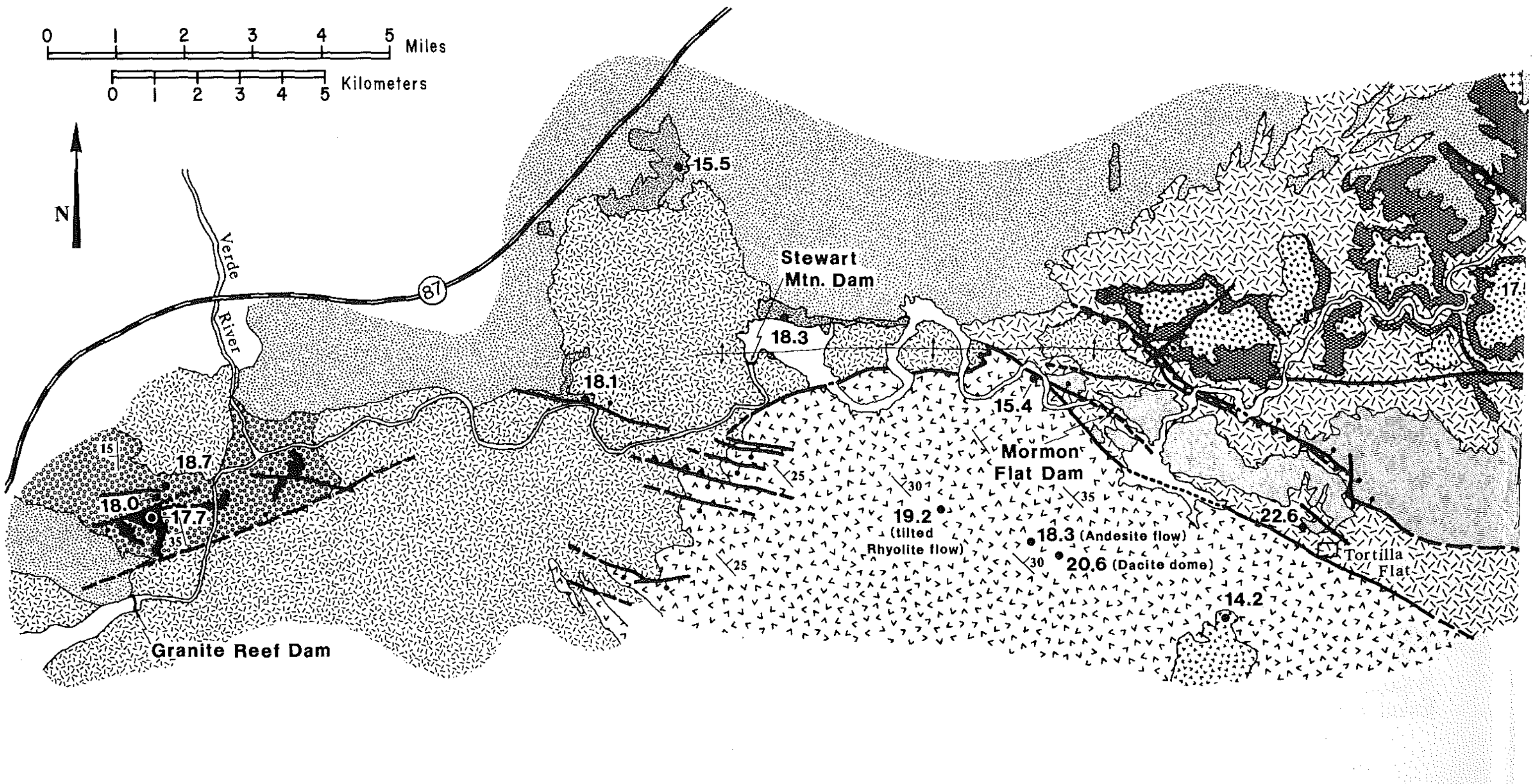
Figure 1 is a generalized geologic map of the region. For the purpose of this report, the geology can be simplified into a fivefold scheme consisting of, from oldest to youngest: an assemblage of Precambrian granite, metarhyolite and sediments, three dissimilar volcanic-sedimentary sections, and capping valley fill sediments separable into two units.

PRE-CENOZOIC ROCKS

Precambrian rocks are extensively exposed along the upstream part of Apache Lake and in the region generally downstream from Stewart Mountain Dam. Along the Salt River course, these rocks consist mostly of a porphyritic quartz monzonite. Along the north shore of Apache Lake, a red metamorphosed rhyolite is also present. The granite is most likely part of the extensive 1.4 billion-year old Ruin-Oracle granite suite of the central Arizona region, and the rhyolite may be related to the 1.7 billion-year old Red Rock Rhyolite found further north. Around Roosevelt Dam, the late Precambrian Apache Group sedimentary rocks are found depositional on the granite as an eastward-dipping block, which disappears under Roosevelt Lake.

It is virtually certain that the Paleozoic and Mesozoic layered

Simplified Geologic Map Along the Salt River Course between Roosevelt and Granite Reef Dams



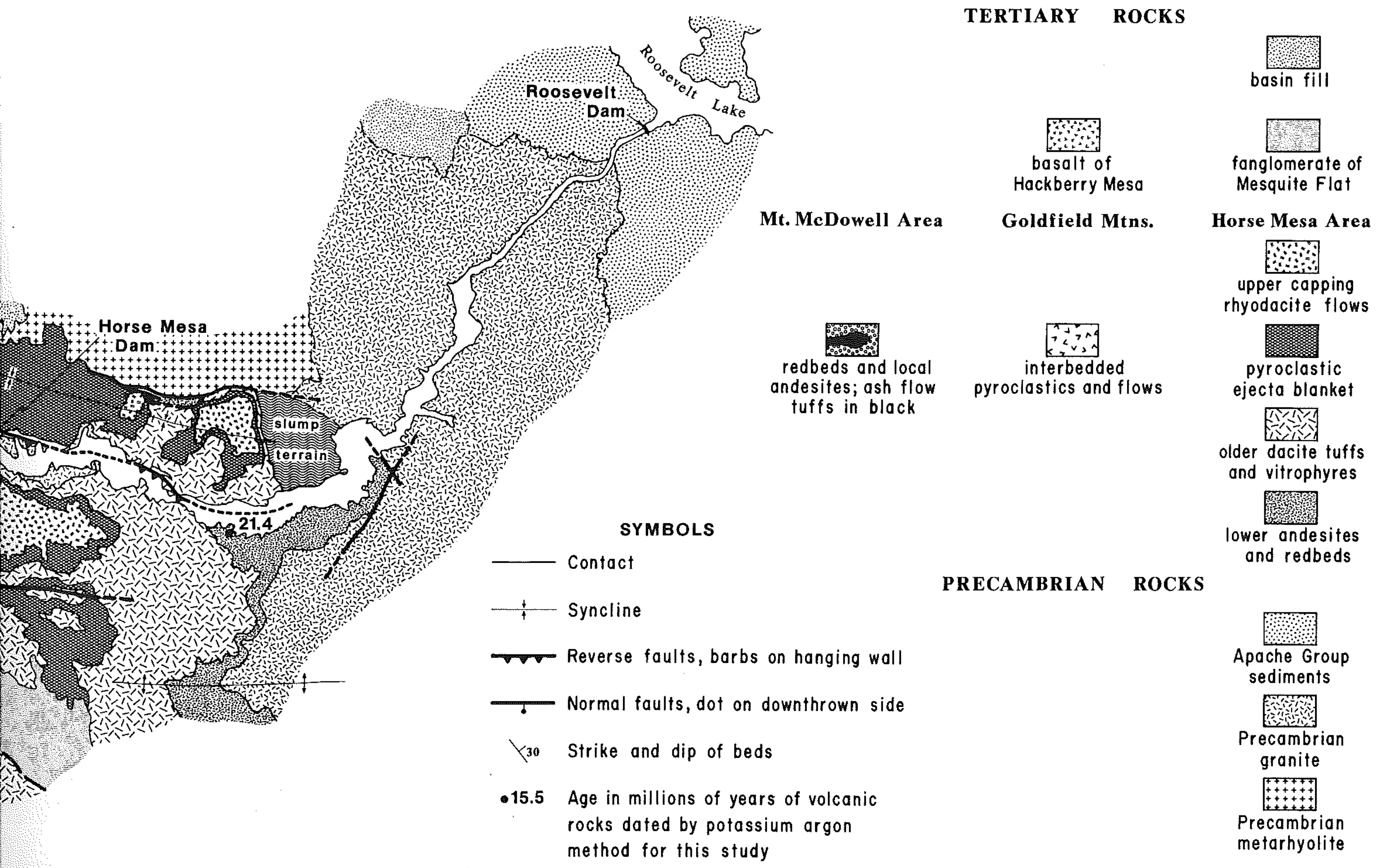
Goldfield and Northern Superstition Mountains

rocks once covered this region, but massive erosion continuing through early Cenozoic time helped to remove these rocks in a broad belt along what is today a transition zone adjacent to the edge of the Colorado Plateau (see Peirce and others, 1979). Sedimentary products of this erosion include the "rim gravels" atop the Mogollon Rim and the Whitetail Conglomerate of parts of southern Arizona.

CENOZOIC VOLCANICS AND SEDIMENTS

The Cenozoic volcanic strata may be divided into three terrains based upon internal stratigraphy and the extent and style of structural deformation. See Figure 1 for their descriptions. The eastern terrain Horse Mesa area of Figure 1 around Canyon and lower Apache Lakes consists of 1) a well-stratified sequence of lower andesites and red fluvial sediments, overlain in turn by 2) a thick section of volcaniclastic mudflows (lahars) which grade westward into vitrophyres and massive, unwelded ash flows (Figure 2), and 3) a series of well-bedded, white-colored air-fall tuffs (Figure 4), 4) upper capping rhyodacite welded ash flows (Figure 4), and 5) an uppermost debris-flow-dominated sediment which has filled an erosionally carved trough or paleovalley centered around Mesquite Flat. The eastern volcanic sequence was deposited against the Precambrian terrain of the southern Mazatzals, but the contact has been highly modified by high angle faulting, as indicated on Figures 1 and 3. Potassium-argon age dates in the volcanic terrain range from 22.6 million years (m.y.) for lower andesites, to 15.4 m.y. for younger, unwelded ash flows along eastern Saguaro Lake. An intermediate-aged, welded rhyodacite ash flow series, which caps Horse Mesa, Goat Mountain and other bluffs in the region around Apache Lake, dates at 17.5 m.y. (Figure 4).

The central volcanic terrain is contained in the main part of the Goldfield Mountains, south of Stewart Mountain and Mormon Flat Dams. It is separated on the map from the eastern terrain for two reasons: The stratigraphy is different in that it consists of a thick series of light yellow-to-white colored air-fall tuffs, mixed with numerous, massive, unwelded and welded rhyodacite flows that weather to very dark brown colors; this stratigraphy is repeated numerous times along NW-trending faults which have served to impart steep NE dips to the strata. These faults may flatten at depth to join a "dislocation surface," which might be represented by the sheared depositional base of the volcanics on granite around lower Canyon Lake. Hence, the tilted nature of this terrain suggests that the volcanics have been laterally transported to the southwest along listric faults (see *Fieldnotes*, 9, (3), p. 14 for a more detailed description of this phenomenon). Homoclinal tilting of the strata does not extend northeast of the boundary between the two volcanic terrains noted in Figure 1. Potassium-argon age dates for rocks in the tilted terrain range from 20.6 to 19.2 m.y., while a younger, untilted basalt flow, which unconformably overlies the tilted flow series, yields a 14.2 m.y. age. This suggests that the tilting event is bracketed between 19.2 and 14.2 m.y. ago (some of these age dates come from Shafiqullah and others, 1980).



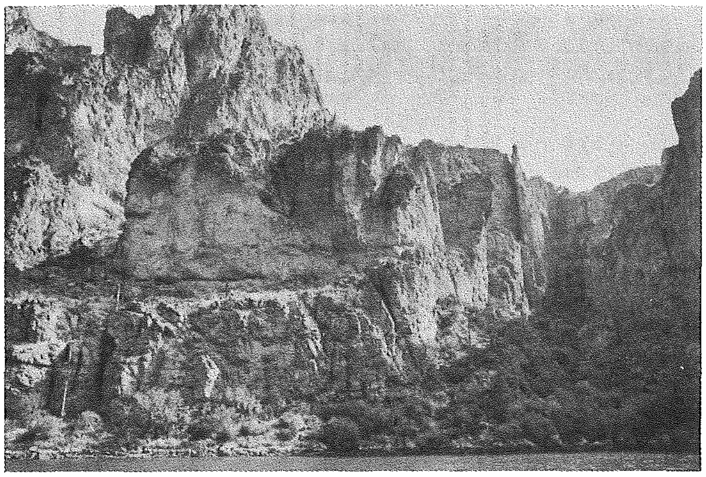


Figure 2. Massive unwelded ash flows exposed along walls of Salt River gorge on Canyon Lake. E-W fault forms spine on skyline.

The Cenozoic section to the west (Mt. McDowell area of Figure 1), between Stewart Mountain and Granite Reef Diversion Dam, is dominated by debris-flow redbeds, with interbedded andesites, trachytes, unwelded ash flows and an upper series of red-colored, wind-deposited sandstones (Figure 5). Around Mt. McDowell (Red Mountain, shown in Figure 6), age dates on enclosed volcanics suggest that the age of these units encompasses 18.7 to 17.7 m.y., but there is considerable stratigraphic section both below and above the dated units. Redbeds and andesites depositionally pinch out to the north against Precambrian granite highs of Arizona Dam Butte (near Orme Dam site) and Stewart Mountain, indicating that these were positive features during the accumulation of these rocks. The southern boundaries of the volcanics in several areas are high-angle fault contacts with granite, along faults which parallel the trend of, and are mostly buried by, the Salt River. Because the redbeds are very thick near the present river course, and are very thin or missing further south, away from the river, it appears that the axis of the present river course is nearly coincidental with the thickest accumulation of redbeds. Several faults that trend nearly E-W around Ft. McDowell and Coon Bluff are normal to the strike direction of the eastward-transported blocks of redbeds and volcanics, and thus, these faults probably served as lateral boundaries to the transported blocks. Listric faults believed to be related to the tilting, trend N-S, but are buried.

CALDERAS OR LARGE FISSURE VENTS?

Sheridan (1978) proposed that the volcanic terrain of the Goldfield-Superstition Mountains is the product of the eruption of three large calderas, each measured in terms of 10–15 miles in diameter. The volcanics of the eastern terrain on Figure 1 correspond to his Tortilla cauldron, and those of the central terrain correspond to parts of his Superstition and Goldfield cauldrons. Sheridan ascribes the faulting and tilting of the volcanics to volcano tectonics, related to bulging and collapse events affecting the terrain over large magma chambers.

Based on observations made during this reconnaissance, the caldera hypothesis does not adequately explain the very dominant NW fault trend, and does not explain certain aspects of the stratigraphy. Perhaps, instead of calderas, several massive fissure vents, each erupting its own characteristic volcanic series, produced an extensive volcanic tableland that was subsequently modified by complex deformation.

OLDER VALLEY FILL

Exposed in the south central part of the area is an older valley fill (fanglomerate of Mesquite Flat) which, at its western extent, is highly involved in block faulting, and is clearly more involved in Miocene tectonics than the overlying basin fill. The valley fill is composed of debris-flow fanglomerates with minor, fluvially sorted sands and gravels with clasts composed of nearly 100 percent Superstition volcanic lithologies. These sediments were deposited in an E-W-trending, erosionally carved basin, and are believed to correlate with a widely distributed set of fanglomerates found elsewhere in southeastern Arizona. The Big Dome Formation and the Apsey Conglomerate nearer Tucson are examples.

BASIN FILL DEPOSITS

Basin fill sediments are the youngest of the major sets of strata. Composed of alluvial fan conglomerates, mudflows and stream channel deposits, this material was derived from adjacent highlands by streams related to the modern drainage system. Except

Figure 3. Fault contact between layered cliff-forming Superstition volcanics (on right, at Goat Mountain) and Precambrian metarhyolite (on left) along north side of Apache Lake. Photo faces east.

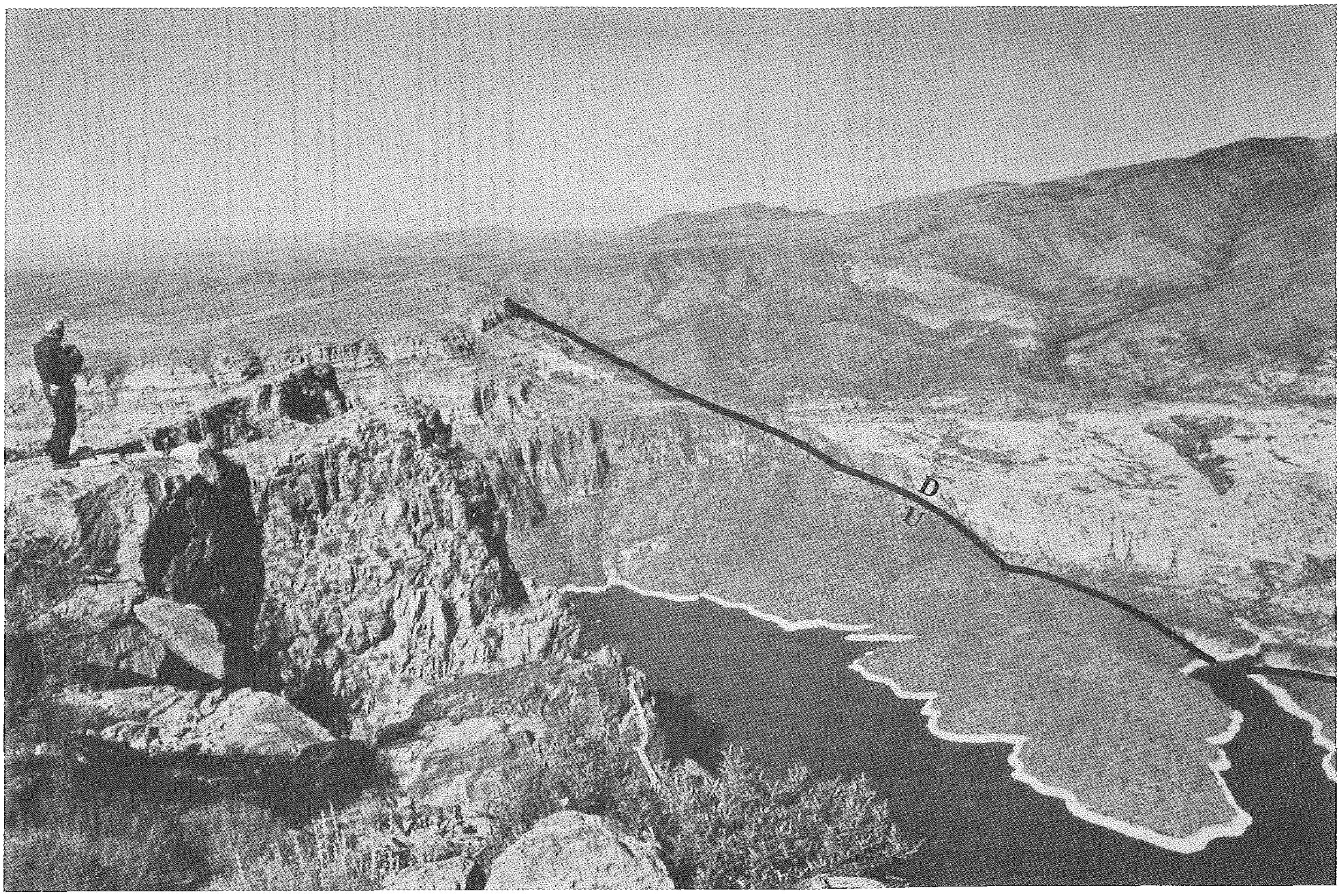


Figure 4. Person stands on upper capping, welded rhyolite flows of Horse Mesa, south of Apache Lake. Across the lake a fault can be seen that offsets a white colored air-fall tuff series. This fault displays reverse (thrust) movement farther upriver. Photo faces north toward western side of Mazatzal Mountains.

near the base, the youngest fill unit is not tectonically deformed. A small patch of basin fill sediments shown on the map, just northwest of Roosevelt Dam and perched at an elevation of up to 3,500 feet, indicates that basin fill covered much of the country adjacent to today's Salt River course, before the cutting of a 2,000 foot deep river gorge through the Superstitions.

FAULTS AND FOLDS

The most obvious fault trends in the region are E-W and WNW, as displayed in Figure 1. Two large faults of WNW trend display some evidence of reverse (compressional) movement (Figures 1 and 4), with an indicated NNE vergence. The more southerly of these two faults displaces the older valley fill unit by several hundred feet, which points to an estimated 12–15 m.y. age for this fault movement. Curious indeed is the roughly synchronous reverse faulting with southwest vergence in the Ray area, 35 miles southeast (S. Keith, pers. comm., 1981) and in the Buckskin Mountains 130 miles to the northwest. It appears that an episode of NE-SW-directed compression, not recognized before at this scale, may have occurred in mid-Miocene time. Several folds, also indicated in Figure 1, have affected the volcanic rocks and Precambrian granite basement in this field area. These folds trend nearly E-W (see Figure 7) and affect rocks as young as the basal part of the basin fill beds that cap the volcanics around Saguaro Lake.

RIVER TERRACES

Several sets of strath terraces, capped by river-deposited gravels and sands, are found above the river throughout the field area. As defined in Péwé (1978), these terraces and their heights above the present Salt-Verde River levels, are the Blue Point Terrace (24–40 feet), the Mesa Terrace (80–300 feet) and the Sawik Terrace (50–100 feet above Mesa Terrace). Figure 7 shows the Mesa Terrace to be about 220 feet above the original river level. Most likely, all these terrace levels are of Pleistocene age (the last 2 m.y.). The Mesa Terrace level is the most traceable of the terraces, and clearly gains elevation in the upstream direction, relative to present river gradient, as pointed out by Péwé. The Mesa Terrace level rises from near floodplain level around Tempe to 250

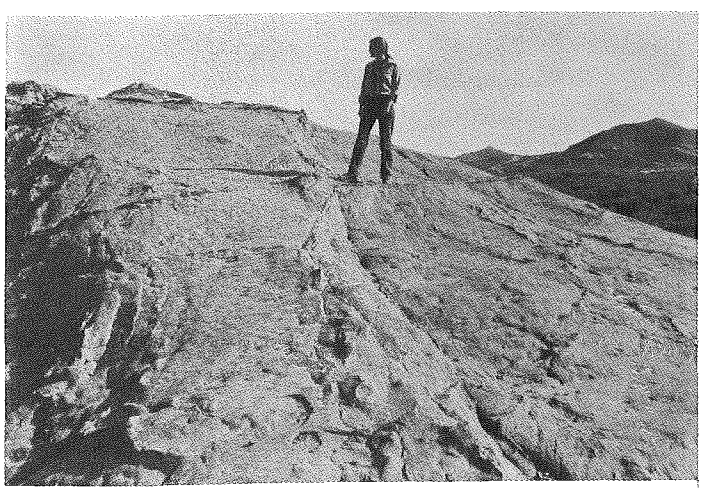


Figure 5. Cross-bedded eolian sandstone (fossil sand dunes) just south of Mt. McDowell, north of Granite Reef diversion dam. These beds rest on the redbeds of Figure 6.

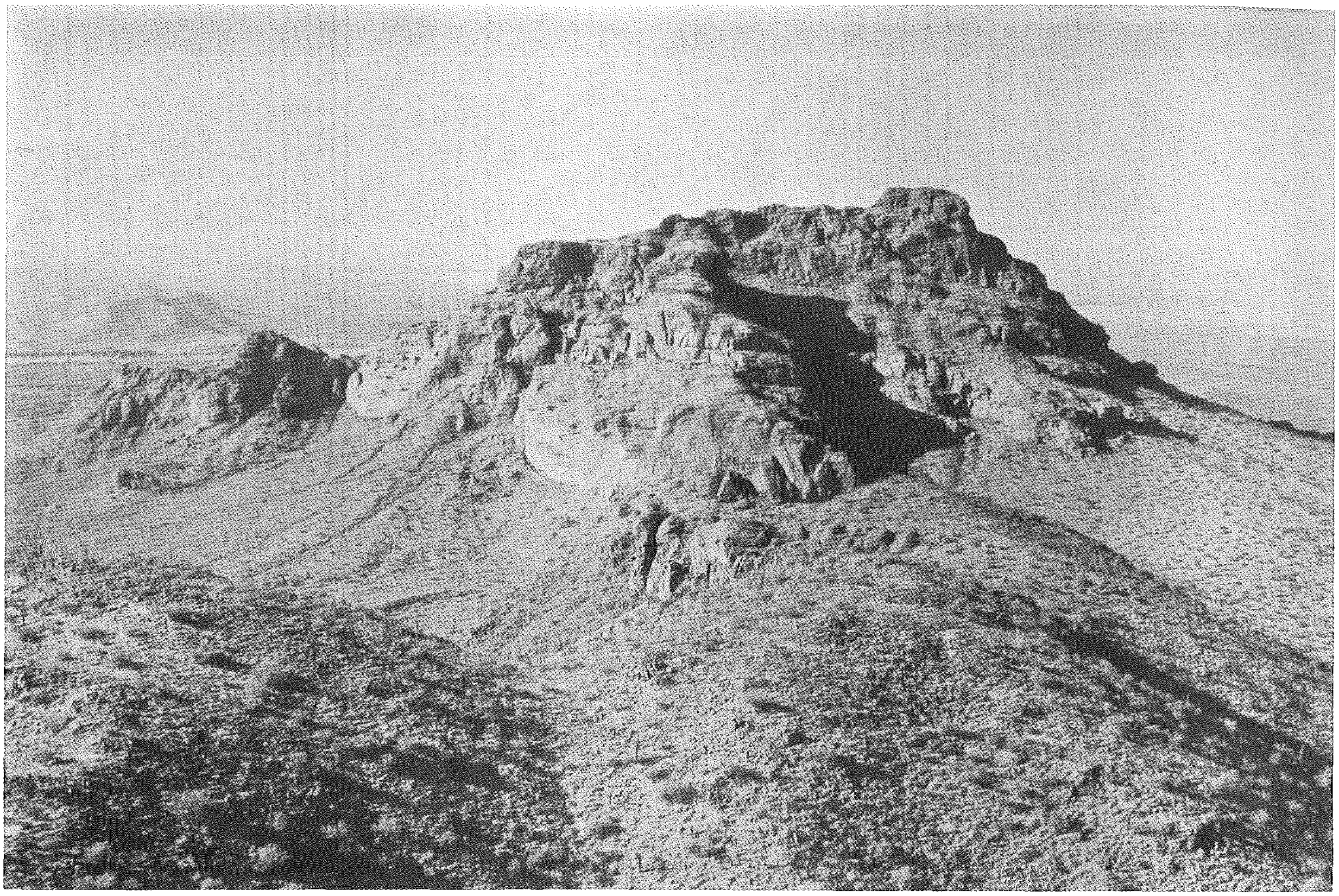


Figure 6. Looking southward at Mt. McDowell (Red Mountain) from over Arizona Dam Butte. The mountain consists of red colored sediments and a few trachyte flows, dipping gently westward. A few patches of redbeds deposited on Precambrian granite are in the foreground.

feet above river level around Apache Lake. This phenomenon can be explained by tectonic upwarping of the mountain region around Lake Roosevelt, with respect to the Phoenix area. However, the possibility also exists that Pleistocene climate changes may have influenced river-carrying capacity and gradient. A more regional picture of terrace levels must be ascertained before deciding on the relative importance of these two factors.

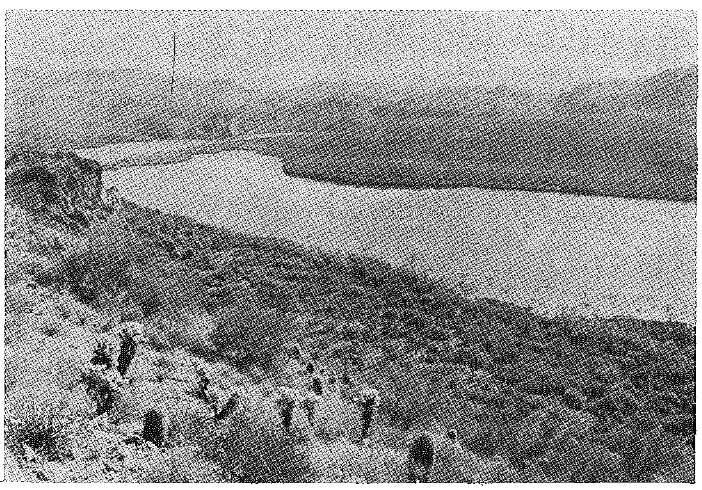


Figure 7. Looking eastward along the axis of the anticline of Saguaro Lake, as depicted on Figure 1. Bagley Flat is across river in mid-ground, consisting of Mesa Terrace River gravels on granite. The granite is exposed only along the anticlinal crest under the volcanic cliffs in the background.

SUMMARY

The region along the lower Salt River contains a vivid story of a massive erosional cycle culminating in early Cenozoic time, of voluminous outpourings of volcanic rocks (such as those recently disgorged from Mt. St. Helens, except on a much larger scale), and of subsequent structural deformation of these rocks by incompletely understood regional forces. The divergence of Pleistocene terraces and modern stream gradients in the region affirm that regional tectonic deformation or climatic cycles, or both, are continuing to modify the record in the rocks.

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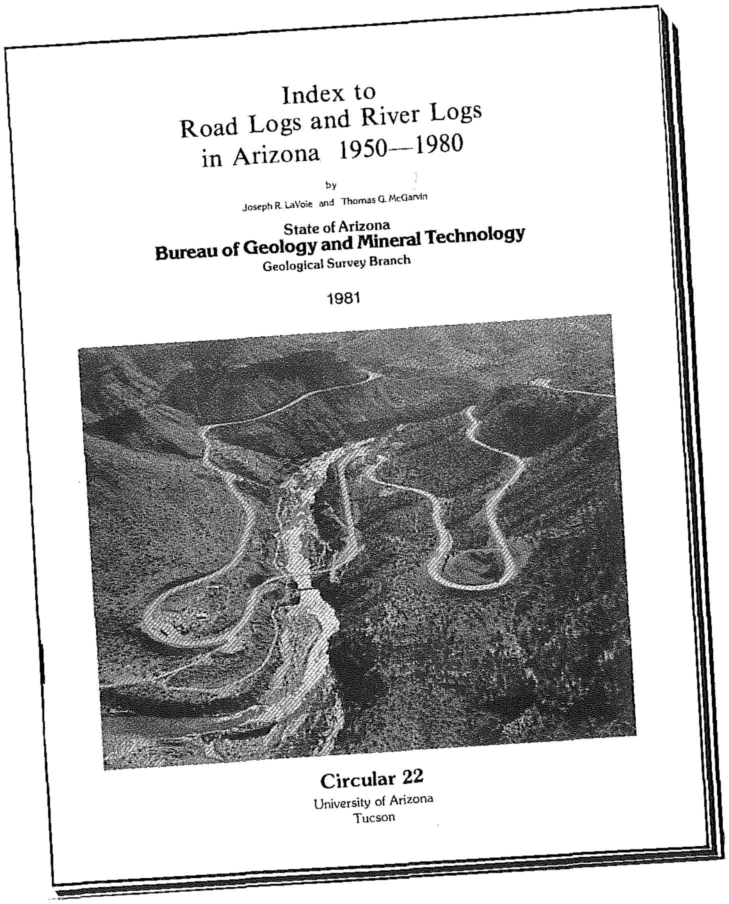
Bob Scarborough has worked for the Arizona Bureau of Geology and Mineral Technology since 1978. He received a B.S. in geology from San Diego State University in 1967 and M.S. in geology from the University of Arizona in 1976. Bob's interests center around Cenozoic geology and tectonics of the western U.S., including Quaternary geology and volcanism in southeastern Arizona.

BUREAU PUBLICATIONS



CIRCULAR 22

Road and River Logs: 1950 – 1980 (maps and bibliography, 14 pages) may be obtained from the Bureau of Geology and Mineral Technology Publications Desk for $1.50 or by mail, with an additional handling charge of 30 cents.

The Arizona Bureau of Geology and Mineral Technology and the University of Arizona's Department of Geosciences have completed a study of *Historical Seismicity in Arizona,* through partial funding provided by the U.S. Geological Survey and the U.S. Nuclear Regulatory Commission. The report was prepared by Susan M. DuBois, geologist at the Bureau of Geology and the Principal Investigator of this project, and by Marc L. Sbar and Thaddeus A. Nowak, Jr., from the Department of Geosciences. *Arizona Earthquakes, 1776–1980* (Bulletin 193) which will include expanded interpretation & results, is currently in progress. *Historical Seismicity in Arizona* is available from the Bureau of Geology as a 199-page Open File Report for $20.00, plus a 20% handling charge if mailed.

MAPS IN PROGRESS

Neotectonic Maps and Analyses in Arizona

Christopher M. Menges, research geologist at the Arizona Bureau of Geology and Mineral Technology, recently completed the systematic mapping of neotectonic (post 3.2 m.y. B.P.) faulting and deformation in Arizona, under contract funding from the USGS, and with the collaboration of consulting geologists, Drs. Roger B. Morrison and Larry K. Lepley.

The analysis is based primarily on uniform, statewide photo-interpretation from black-and-white U2 photography, supported by extensive ground and low-altitude aerial reconnaissance. Available published and unpublished literature sources have been compiled as well. The final products include two primary maps: 1) a 1:500,000 scale map of proven, probable and possible late Pliocene-Quaternary faults; and 2) a 1:1,000,000 scale map of known areas of Pliocene-Quaternary uplift, subsidence and deformation in Arizona, with an accompanying set of tables and reference lists. These maps are currently undergoing technical review at the USGS and the Arizona Bureau of Geology.

Chris Menges is presently engaged in further refinement of the existing neotectonic maps and expanded analysis of neotectonics in the state. This project, contracted by the USGS, is scheduled for completion in the fall of 1982; it consists of several phases, including preparation of late Cenozoic (post mid-Miocene) tectonic maps of Arizona, stratigraphic and geomorphic studies of the major fault scarps, regional analysis of tectonic geomorphology, and comparisons between neotectonic deformation and older, relevant data sources. The results will be presented in a final report with accompanying maps.

Quaternary Map of Arizona

Dr. Roger B. Morrison and Chris Menges are currently involved in regional mapping of the Quaternary geology of Arizona, with funding from the USGS. The U2 photo-interpretation, supported by ground reconnaissance and compilation of relevant, existing data, will be displayed in generalized form within a 1:1,000,000 scale map. More detailed 1:250,000 scale maps will be available for inspection at the Bureau of Geology. These maps will depict generalized time-stratigraphic Quaternary units arranged within various alluvial, lacustrine, and eolian lithofacies subdivisions. Quaternary volcanic rocks will also be shown. This project is scheduled for completion by spring 1982.

NATIONAL/REGIONAL/LOCAL EVENTS

Geological Society of America—Annual Meeting, Rocky Mountain Section, Bozeman, May 7–8, 1982.

Geological Society of America & Seismological Society of America—Annual Meeting, Cordilleran Section, Anaheim, April 19–21, 1982.

Colorado School of Mines—International Conference on Geological Information, Golden, May 24–28, 1982.

American Geophysical Union—Spring Meeting, Philadelphia, May 31–June 4, 1982.

American Association of Petroleum Geologists and **Society of Economic Paleontologists and Mineralogists**—Annual Meeting, Calgary, June 27–July 1, 1982.

University of California—Rock Mechanics Symposium, Berkeley, August 25–27, 1982.

University of Arizona, Geosciences Department—Geoscience Daze, Tucson, March 24–26, 1982.

NEW PUBLICATIONS

The Arizona Atlas, by Melvin E. Hecht and Richard W. Reeves, University of Arizona Department of Geography and Regional Development: Published by University of Arizona Office of Arid Lands Studies, Tucson (164 p.). $12.95

"The focus of this atlas is Arizona's people ... the distribution of Arizona's inhabitants ... "[in relation to the state's sociological, economic, historical, physical, political environment] (*from* the Preface).

Geology of Arizona, by Dale Nations, Professor of Geology at Northern Arizona University, and Edmund Stump, Associate Professor of Geology at Arizona State University: Kendall/Hunt Publishing, Dubuque, (210 p.). $9.95

This publication "is organized with an assumption that the reader has no formal training in geology, with a brief treatment of materials and processes, rock types, stratigraphic principles, structure and tectonics, land forms and geologic time, in the first few chapters. Subsequent chapters discuss the geologic character of Arizona and its geologic history." (*from* Preface).

The Department of Geology and Geophysics at the University of Wyoming has recently published the "Geologic Map of the Hurricane Fault Zone and Vicinity, Western Grand Canyon, AZ" (Huntoon & Billingsley). This 1:48,000 scale map may be ordered from the Plateau Mapping Project, P.O. Box 3681, Laramie, WY 82071. Single, rolled copies are $8 each; additional maps mailed together are $6.50 each.

A three-part, 2,133-page volume on water resource data in 10 western states has been compiled by the USGS, in cooperation with the U.S. Office of Surface Mining (OSM). This publication is the third of a five-volume series entitled, *Index to Water-Data Acquisition in the Coal Provinces of the United States*. Copies may be reviewed at any USGS Water Resources Divisions or OSM district or field offices in the following states: Arizona, Colorado, Idaho, Montana, New Mexico, North Dakota, Oklahoma, South Dakota, Utah and Wyoming. Further information on this series may be obtained from the USGS National Center, Reston, VA (703/860-6931) or OSM (202/343-4264) in Washington, DC.

The American Association of Petroleum Geologists has published five 1:10 million-scale plate-tectonic maps of the Circum-Pacific region (Northwest, Northeast, Southeast, and Southwest quadrants, and Antarctica). These maps may be purchased from the AAPG Bookstore, P.O. Box 979, Tulsa, 74101 at $8 each or $26 per set.

Fieldnotes

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